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# Notched marble plates under direct tension: Mechanical response and fracture

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## HIGHLIGHTS

- Direct tension, bending and Brazilian tests provide different tensile strength.
- The axial stress-strain curve of Dionysos marble strongly deviates from linearity.
- Critical Notch Opening Displacement appears inappropriate as fracture criterion.
- Both mode-I and II phenomena appear during direct tension of marble DENT specimens.
- The AE technique permits crack classification both in simple and complex structures.

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## ABSTRACT

The mechanical response of notched marble plates under direct tension is studied experimentally. The motive of the study emerges from the needs of scientists working for restoration of marble monuments, the structural elements of which are often damaged and cracked. The specimens are made of Dionysos marble, used for the restoration of the Athenian Acropolis monuments. The aim of the study is two-folded: Description of the material's overall mechanical response in the presence of macroscopic discontinuities and mapping the damage evolution process. Modern (Digital Image Correlation, Acoustic Emissions, Ultra High Speed Camera) and traditional sensing techniques were used in a combined manner. Concerning the overall mechanical response it was concluded that the size effect is extremely pronounced while the critical Notch Opening Displacement appears inappropriate as a fracture parameter. Analysis of the data pumped with the aid of the Acoustic Emissions technique enlightened crucial aspects of the damage mechanisms activated, indicating simultaneous generation of both tensile- and shear-cracking modes, attributed to the layered structure of Dionysos marble.



## 1. Introduction

The response of structures or structural members to mechanical loads, at levels approaching those causing failure, concerns seriously the engineering community. The issue is closely related to the classical question concerning the remaining life (equivalently the remaining load carrying capacity) of structures and structural elements. Among the fields for which a clear answer to this question is even more imperative is that of restoration of stone monuments. This is because their structural elements are usually damaged and seriously cracked. In such a case the question reads differently: "*Is it possible to predict when a cracked structural member is going to fail by initiation and catastrophic extension of a pre-existing defect either in the form of a crack or a notch?*" This question is, in fact, the very heart of Fracture Mechanics. Unfortunately, a series of practical restrictions of the restoration praxis makes the problem much more complicated: In most cases the actual load level induced on a monument's structural member is not a priori known and therefore standard crack initiation criteria of Fracture Mechanics are not applicable. In addition, installation of traditional strain/displacement sensing and recording devices on structural members of monuments is not desirable (or even is not permitted at all) for obvious aesthetic and cultural reasons, rendering Structural Health Monitoring (SHM) quite a challenging task.

A typical example of the above discussion is the Acropolis of Athens: All monuments on the "sacred rock" of the Athenian Democracy are built from Pentelic marble blocks. Most of their structural members are, nowadays, damaged and their load carrying capacity is questionable. This is clearly shown, for example, in

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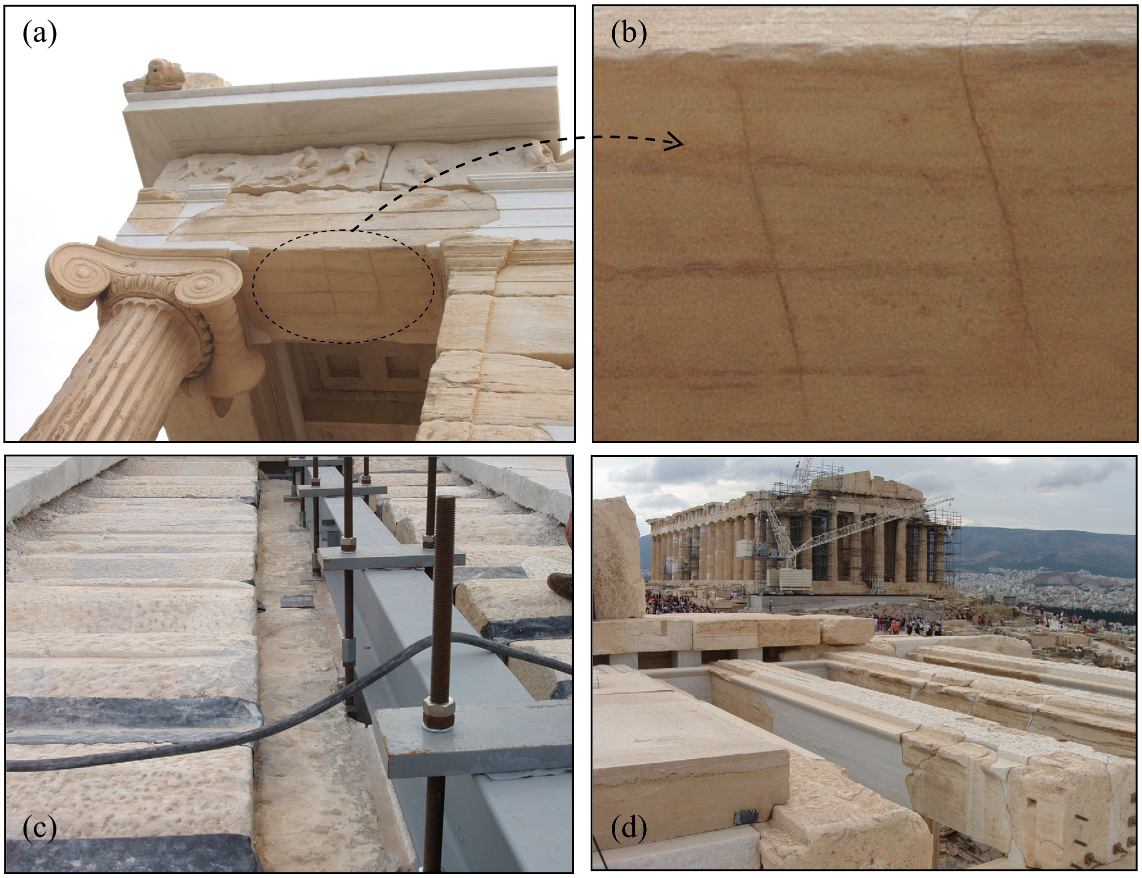


**Fig. 1.** (a) A restored epistyle of the Propylaea of the Athenian Acropolis; (b) Enlarged view showing cracks running almost through the whole width; (c) The metallic structure improvised by the engineers working for the restoration of the monument to ensure the stability of the restored epistyle; (d) Co-existence of old (authentic) and freshly quarried marble together with metallic connectors creating a three material complex with various interfaces making analytic determination of strain or displacement fields prohibitively difficult.

Fig. 1, where one of the huge epistyles of the Propylaea (i.e., the main "entrance" of the Acropolis monuments complex) is shown, in its restored form. In the magnified view of this epistyle, shown in Fig. 1b, one can clearly distinguish, even by naked eye, two cracks, running almost through the width of the epistyle, raising major concerns about the stability of the member. It must be emphasized at this point that the scientists working for the project have already confronted the problem by suitably suspending the member from its upper side with a very cleverly designed, invisible to the visitor, metallic scaffold, shown in Fig. 1c.

Quite a few epistyles of the Acropolis monuments are also cracked in a similar manner [1] and it is imperative for the restoration personnel to in-situ monitor their behaviour, in order to timely detect even the slightest change of the cracks' length. It is evident that any solution of the problem based on theoretical principles of Fracture Mechanics is beyond any discussion: The geometry of the members and the coexistence of old (authentic) and new (substitute) marble (Fig. 1(a and d)) together with metallic connectors creates a number of interfaces making things far too complicated and any attempt to analytically determine strain or displacement fields prohibitively difficult. Moreover, any failure/damage mechanism is firstly activated along the above interfaces (marble-to-marble, marble-to-filling mortar, mortar-to-metallic connectors) in the interior of the member, well before any macroscopically visible crack is observable at the external surface of the member.

Recapitulating, it can be said that in order for questions regarding the remaining load-carrying capacity of restored structural elements of classical monuments to be answered, data are required, which can be only gathered experimentally, mainly from the interior of the element. In addition these data should be obtained with the aid of sensors which must be cheap, accurate, reliable, easy-to-use and also of very small size, since they should not destroy the aesthetic splendor of these unique monuments of Cultural Heritage. However, it is common place in Experimental Strength of Materials that traditional experimental techniques for measuring strains and displacements (strain gauges, dial gauges, clip-gauges, extensometers, photo-elasticity, Moiré patterns, caustics etc.) provide data obtained exclusively from the external surface of the specimens. In this context, devising and using novel experimental systems, which could provide data from the interior of the members (specimens) during the whole loading process, appears imperative. Among these systems, the detection of Acoustic Emission (AE) events is perhaps the most widely used one.

In the direction of providing some answers to the above open questions, an experimental protocol was designed with notched marble plates subjected to uniaxial tension. The full-field displacement components developed are recorded using the Digital Image Correlation (DIC) technique while the Notch Mouth Opening Displacement (NMOD) is also recorded using clip-gauges. Electrical resistance strain gauges were used, in some tests, to measure the strain components at strategic points on the specimens while Linear Variable Differential Transformers (LVDTs) and dial gauges were used to quantify parasitic rigid body motions of the specimens (mainly rotations, caused by the way the specimens were attached to the loading frame). An Ultra High Speed Camera (UHSC) was used to capture the onset and propagation of fracture which in case of marble is rapid. Finally the AE technique was used to monitor the spatiotemporal development of internal damage.